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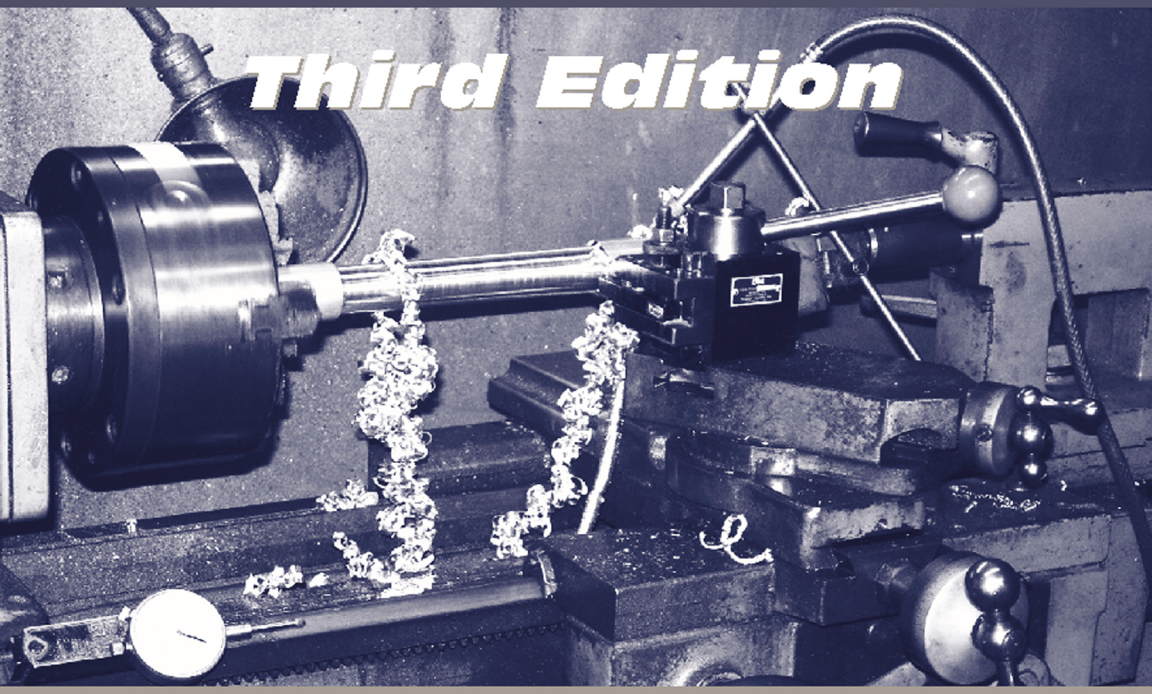

Third Edition

Geoffrey Boothroyd
Winston A. Knight

Fundamentals of Machining and Machine Tools

Third Edition

MANUFACTURING ENGINEERING AND MATERIALS PROCESSING

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Third Edition

Geoffrey Boothroyd
Boothroyd Dewhurst, Inc.
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Kingston, Rhode Island

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Preface to Third Edition

Similar to the previous editions, this book is intended for those studying and teaching the principles of machine tools and machining in universities and colleges, as well as providing a useful background for those involved in manufacturing in industry.

Since the second edition was published in 1989, there have been some significant developments in the analytical modeling of machining processes, together with changes in machining practice in industry, in particular as a result of developments in modern cutting tool materials. For this reason most of the chapters in the book have been updated to reflect these recent developments.

As in previous editions, the mathematical content of the book has been limited, but it was found appropriate to include some description of modern analytical methods that can be applied to machining, in particular to outline the capabilities and limitations of the various modeling approaches. The chapter on tool materials and tool life has been updated to reflect the recent developments in super hard cutting tool materials, tool geometries, and surface coatings. These new tool materials have enabled cutting speeds to be increased significantly and have led to more effective machining of difficult to cut work materials. For this reason some description of developments in high speed machining and hard machining has been included.

The chapter on cutting fluids has also been updated to include developments in cutting fluid applications, including the trends towards dry and minimum-quantity lubrication machining. Similarly, the chapter on chip control has been modified to reflect developments in tool geometries for chip breaking and chip control.

As in the previous editions, significant emphasis is placed on the economics of machining processes and design for machining. This material has been expanded to include improvements in the cost modeling of machining processes, including the application to grinding processes.

We are indebted to those we have been associated with in recent years and who have contributed both directly and indirectly in the preparation of this book, including colleagues and graduate students whose work has been helpful. The discussion on planning for multispindle automatics in Chapter 11 is derived from the Master of Science thesis of Jeremy Young and the procedures for determining recommended cutting conditions in Chapter 6 are based on the Master of Science thesis of Richard Turner. We are also grateful to Brian Rapoza of Boothroyd Dewhurst Inc. for developing the empirical equations for laser and plasma cutting used in Chapter 14.

Winston Knight

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Preface to Second Edition

This book is intended primarily for those studying and teaching the principles of machine tools and metal machining in universities and colleges. It should also prove useful to those concerned with manufacturing in industry.

The mathematical content of the book is deliberately limited. Those who have taken basic courses in statics and dynamics and who have had an introduction to calculus should have no difficulty in comprehending the material.

Many of the present texts dealing with the same material are purely descriptive. In this book, the approach is to illustrate, through fundamentals and analysis, the causes of various phenomena and their effects in practice. Emphasis is given to the economics of machining operations and the design of components for economic machining.

A significant portion of the book is based on a previous text written by one of the authors (Geoffrey Boothroyd) and published by McGraw-Hill. While much of this material has been retained, recent developments have been included where appropriate. Several new chapters have been introduced and others largely rewritten. The section on tool materials has been expanded to include the modern materials that are contributing significantly to increases in productivity in industry. A new chapter on machine tool vibrations has been included, which covers the fundamental aspects of machine tool chatter, the dynamic testing of machine tools, and the practical means of improving machine tool stability. The chapter on grinding has been expanded to include thermal aspects of the process and a description of new grinding processes, including creep feed grinding.

New emphasis in the book has been placed on the utilization of machine tools through the inclusion of chapters on manufacturing systems and automation and on computer-aided manufacturing, together with an expanded chapter on design for machining, which serves as an introduction to an area of growing importance, that of design for manufacturability. Various types of automation in machine tools are outlined and an introduction to cellular plant layouts and flexible manufacturing systems is included. Aspects of the programming of numerical control machine tools are discussed in some detail. Finally, because of their growing importance, the main nonconventional machining processes are described and examples of their application given.

We are indebted to those with whom we have been associated in recent years and who have assisted both directly and indirectly in the preparation of this book, including colleagues and graduate students whose work has been helpful in the preparation of this book. Finally, we would like to thank Kathleen Yorkery for typing the manuscript.

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Conventions Used in This Book

STANDARDIZATION

Every attempt is made in this book to follow the International Organization for Standardization (ISO) recommendations for units and definitions. The most important of these is, of course, the International (SI) System of basic and derived units. The basic system is described in ISO Standard 1000, and recommendations for its application are specified in ISO Recommendation R31. The latter document includes suggested symbols for the various derived units.

In addition, numerous standards are becoming available covering various aspects of machining and are followed as closely as possible. Unfortunately, some of these new standards include symbols and definitions that are at variance with the SI; this variance leads to a certain amount of duplication. For example, the recommended symbol for the feed applied in a machining operation is *f*, which is also the recommended symbol for frequency of vibration. Confusion among measurements and symbols is avoided, however, by the use of appropriate suffixes and subscripts, respectively.

This book is written mainly in SI units because many U.S. manufacturing industries now work in the SI system. However, a nationwide conversion to the metric system is not expected in the foreseeable future. For this reason, in most cases where SI units are specified in the text, the approximate English (U.S. Customary System [USCSI]) equivalents are given in parentheses. Graphs and results from previously published work are reproduced with the original scales in English (USCS) units, and the corresponding SI scales are added at the right and along the top where appropriate. Graphs produced specifically for this book are given in SI units with the equivalent English units added at the right and along the top. In some places English units are used in the text and the appropriate conversion factors are given. This is particularly the case for Chapter 13.

INTRODUCTION TO THE INTERNATIONAL (SI) SYSTEM OF UNITS

In 1960 the General Conference of Weights and Measures on the International System of Units formally approved the system of units known as the International (SI) System of Units. This system is now adopted for most countries throughout the world, but it is currently not being adopted by the United States, although many international companies have standardized on the system. In practice the

system is convenient because it obviates the need for the insertion of conversion factors into equations and eliminates many of the ambiguities present in other systems. The basic SI units encountered in engineering are defined as follows:

1. The unit of length *l* is the meter, m, which is the length equal to 1, 650,763.73 wavelengths in vacuo of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton-86 atom.
2. The unit of mass *m* is the kilogram, kg, which is equal to the mass of the international prototype of the kilogram.
3. The unit of time *t* is the second, s, which is the duration of 9, 192, 631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.
4. The unit of temperature *T* is the kelvin, K, which is 1/273.16 of the thermodynamic temperature of the triple point of water.
5. The unit of electric current *I* is the ampere, A, which is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible, circular cross section and placed 1 meter apart in a vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length.

To encourage the student or reader to become familiar with SI units, most of the problems presented at the end of each chapter are given in SI units without the English equivalents. It is hoped that the student or reader will thereby discover that the new system is considerably easier to work with than the U.S. Customary System (pounds, feet, etc.).

For those not sufficiently familiar with the SI system, the tables introduce the basic and derived units and their definitions and recommended symbols. Useful conversions are also given.

Table SI.1 presents a selection of derived units.

The most common prefixes for SI units are listed in Table SI.2. It should be noted that:

1. The prefix refers to the whole unit; for example, the m (milli) in $m.N/m^2$ means $m(N/m^2)$, not mN/m^2. The dot is used to indicate multiplication when confusion could arise.
2. Prefixes in denominators are avoided, except for k in kg (kilogram).

Useful conversion factors are given in Table SI.3.

TABLE SI.1
Units Derived from the Basic SI Units

Unit Being Measured	Symbol	Name of Unit	Symbol of Unit
Angle, plane	α, β, γ, etc.	Radian	rad
Angular velocity	ω	—	rad/s
Angular acceleration	α	—	rad/s^2
Frequency	*f*	Hertz	Hz
Rotational frequency	*n*	Reciprocal second	s^{-1}
Area	*A*	—	m^2
Volume	*V*	—	m^3
Velocity	*v*	—	m/s
Acceleration	*a*	—	m/s^2
Density	ρ	—	kg/m^3
Force	*F*	Newton	N
Energy, work, heat	*W*	Joule	N.m or J
Pressure, stress	*p*	Pascal	N/m^2 or Pa
Power	*P*	Watt	J/s or W
Temperature difference	θ	Degree Celcius	K-273.15 or °C

TABLE SI.2
Prefixes Used for SI Units

Multiple and Sub-Multiple[a]	Prefix	Symbol
10^9 or $E + 09$	giga	G
10^6 or $E + 06$	mega	M
10^3 or $E + 03$	kilo	k
10^{-3} or $E - 03$	milli	m
10^{-6} or $E - 06$	micro	μ
10^{-9} or $E - 09$	nano	n
10^{-12} or $E - 12$	pico	p

[a] $E \pm ab = 10^{\pm ab}$

TABLE SI.3
USCS — SI Conversion Table

Quantity	To Convert From	To	Multiply By[a]	
Length	inch (in.)	meter (m)	2.54*	*E* – 02
	foot (ft)	meter (m)	3.048*	*E* – 01
Mass	pound (lb)	kilogram (kg)	4.535 924	*E* – 01
Time	minute (min)	second (s)	6.0*	*E* + 01
	hour (hr)	second (s)	3.6*	*E* + 03
Force	pound force (lbf)	newton (N)	4.448 222	*E* + 00
Speed	foot per minute (ft/min)	meter per second (m/s)	5.08*	*E* – 03
	inch per second (in./s)	meter per second (m/s)	2.54*	*E* – 02
	inch per minute (in./min)	meter per second (m/s)	4.233*	*E* – 04
	revolution per minute (rpm)	radian per second (rad/s)	1.047 192	*E* – 01
Acceleration	foot per second per second (ft/s^2)	meter per second per second (m/s^2)	3.048*	*E* – 01
	inch per second per second ($in./s^2$)	meter per second per second (m/s^2)	2.54*	*E* – 02
Area	square inch ($in.^2$)	square meter (m^2)	6.451 6*	*E* – 04
Volume	cubic inch ($in.^3$)	cubic meter (m^3)	1.638 706	*E* – 05
Volume flow rate	cubic inch per minute ($in.^3/min$)	cubic meter per minute (m^3/min)	2.731 177	*E* – 07
Density	pound per cubic inch ($lb/in.^3$)	kilogram per cubic meter (kg/m^3)	2.767 991	*E* + 04
Pressure, stress	pound force per square inch ($lbf/in.^2$)	newton per square meter (N/m^2)	6.894 757	*E* + 03
Energy, work, heat	British thermal unit (Btu)	newton-meter (N-m) or (J)	1.055 06	*E* + 03
Power	horsepower (hp)	joule per second (J/s) or (W)	7.457	*E* + 02
	foot-pound force per minute (ft-lbf/min)	joule per second (J/s) or (W)	2.259 697	*E* – 02
Thermal conductivity	Btu in./hr ft^2 °F	joule per second meter kelvin (J/smK), or watt per meter kelvin (W/mK)	1.442 279	*E* – 01
Specific heat capability	Btu/lb °F	joule per kilogram kelvin (J/kgK)	4.148	*E* + 03

[a] Values followed by an asterisk are exact conversions.

1 Machine Tools and Machining Operations

1.1 INTRODUCTION

The history of metal cutting dates from the latter part of the eighteenth century. Before that time machine tools did not exist, and the following extract from the diary of an English engineer, Richard Reynolds, dated October 1760, gives some idea of the manufacturing problems that had to be faced. Richard Reynolds was attempting to produce a cylinder for a tire engine for drawing water from a coal pit. The cylinder, of cast brass, had a length of 9 ft and a bore 28 in. in diameter. He wrote:

> Having hewed two balks of deal to a suitable shape for the cylinder to lie therein solidly on the earth in the yard, a plumber was procured to cast a lump of lead of about three hundred weight, which being cast in the cylinder, with a dike of plank and putty either side, did make it of a curve to suit the circumference, by which the scouring was much expedited. I then fashioned two iron bars to go around the lead, whereby ropes might be tied, by which the lead might be pulled to and fro by six sturdy and nimble men harnessed to each rope, and by smearing the cylinder with emery and train oil through which the lead was pulled, the circumference of the cylinder on which the lead lay was presently made of a superior smoothness: after which the cylinder being turned a little, and that part made smooth, and so on, until with exquisite pains and much labour the whole circumference was scoured to such a degree of roundness as to make the longest way across less than the thickness of my little finger greater than the shortest way: which was a matter of much pleasure to me, as being the best that we so far had any knowledge of.

In 1776 James Watt built the first successful steam engine, and one of his greatest difficulties in developing this machine was the boring of the cylinder casting. His first cylinder was manufactured from sheet metal, but it could not be made steam tight. Even attempts to fill the gap between the piston and the cylinder with cloth, leather, or tallow were of no avail. John Wilkinson eventually solved the problem when he invented the horizontal-boring machine. This machine consisted of a cutting tool mounted on a boring bar that was supported on bearings outside the cylinder. The boring bar could be rotated and fed through the cylinder. Thus generating, with the tool points, a cylindrical surface independent of the irregularities of the rough casting (Figure 1.1). This boring machine was the first effective machine tool, and it enabled James Watt to produce a successful steam engine.

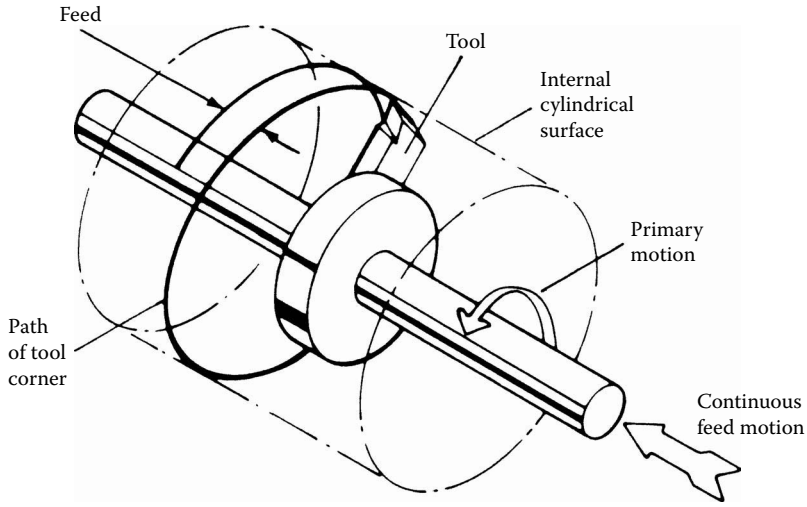


FIGURE 1.1 Generation of a cylindrical surface in horizontal boring.

Metal cutting, as we know it now, started with the introduction of this first machine tool. Today, machine tools form the basis of our industry and are used either directly or indirectly in the manufacture of all the products of modern civilization.

1.2 GENERATING MOTIONS OF MACHINE TOOLS

The principle used in all machine tools is one of generating the surface required by suitable relative motions between the cutting tool and the workpiece. The cutting edge or edges on the cutting tool remove a layer of work material; the removed material is called a shaving or a chip. The simplest surfaces to generate are flat surfaces and internal or external cylindrical surfaces. For example, if a tool is reciprocated backward and forward in a straight line and a workpiece is incrementally fed beneath the tool in a direction at right angles to the motion of the tool, a flat surface will be generated on the workpiece. Similarly, rotating the workpiece and feeding the tool parallel to the axis of workpiece rotation can generate a cylindrical surface. Thus, in general, two kinds of relative motion must be provided by a metal-cutting machine tool. These motions are called primary motion and feed motion and are defined as follows:

The primary motion is the main motion provided by a machine tool or manually to cause relative motion between the tool and workpiece so that the face of the tool approaches the workpiece material. Usually, the primary motion absorbs most of the total power required to perform a machining operation.

> The feed motion is a motion that may be provided to the tool or workpiece by a machine tool which, when added to the primary motion, leads to a repeated or continuous chip removal and the creation of a machined surface with the desired geometric characteristics. This motion may proceed by steps or continuously; in either case it usually absorbs a small proportion of the total power required to perform a machining operation.

To facilitate the descriptions of machine tool motions it is useful to employ a system of machine tool axes recommended by the International Organization for Standards (ISO) [1]. Although this system was established for the purposes of programming numerically controlled machine tools, it is suitable as a general system for all machine tools. The system is based on the right-hand coordinate system shown in Figure l.2a and refers to the possible motions of a tool in a machine tool. The three coordinate axes X, Y, and Z refer to possible linear motions of the tool, and the motions A, B, and C refer to possible rotary motions of the tool about these axes, respectively. To understand the right-hand screw sign convention used in this system, it is helpful to imagine a right-hand screw thread aligned with each axis. If a screwed nut mounted on any axis is rotated such that it moves along the axis in a positive direction away from the origin, that rotary motion is positive.

A particular machine tool can move the tool in only a few of the possible directions shown in Figure l.2a. However, before the actual directions of motion in a particular machine tool can be labeled, it is necessary to orient the coordinate system relative to that machine tool. The coordinate system is oriented as follows:

The Z axis of motion is arranged parallel to the axis of the machine spindle, which provides primary motion. If the machine has no spindle, the Z axis is arranged perpendicular to the work-holding surface. Positive Z motion increases the distance between the workpiece and tool holder.

Where possible, the X axis is horizontal and parallel to the work-holding surface. On machines with no main spindle, the X axis is parallel to and positive in the principal direction of cutting (primary motion). On machines with rotating workpieces, the X motion is radial and parallel to the cross slide. (Positive X motion is defined as the motion of a tool when it recedes from the axis of rotation of the workpiece.) On machines with rotating tools:

1. If the Z axis is horizontal, positive X motion is to the right when viewed from the main spindle toward the workpiece.
2. If the Z axis is vertical, positive X motion is to the right when viewed from the main spindle toward the machine column.

Positive Y motion is selected to complete the coordinate system shown in Figure l.2a.

For motion of the workpiece in a machine tool, a similar set of axes and motions is employed (Figure l.2b), but the appropriate letter is primed, and the

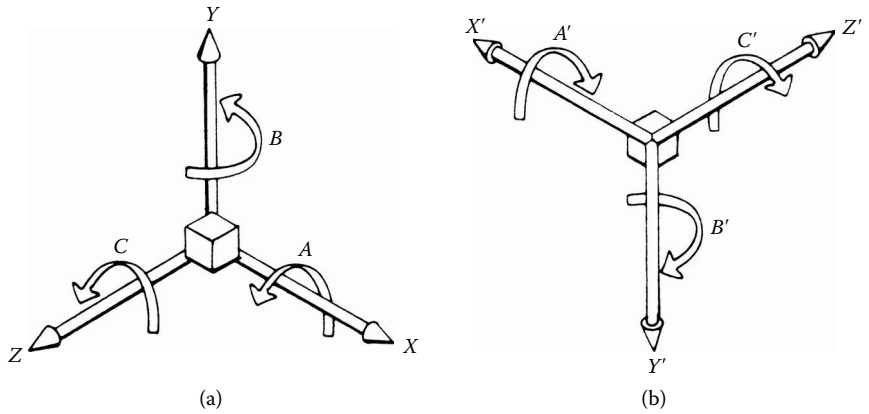


FIGURE 1.2 Coordinate system for specification of machine tool motions. (a) Motions of the tool; (b) motions of the workpiece.

sign convention is reversed. The reason for the prime and reversed sign is that if, for example, a tool can be made to approach a workpiece by motion in the positive X direction, the same effect can be obtained by moving the workpiece in the positive X′ direction.

In the following sections some common general-purpose low-production machine tools will be described and their generating motions illustrated. The same basic motions are also used in higher productivity and automatic machine tools and description of machines of this type can be found in Chapter 11. Machine tools in general can be divided into three groups:

1. Those using single-point tools
2. Those using multipoint tools
3. Those using abrasive wheels

Machines using single-point tools will be described first, starting with the most common, the engine lathe. The description of the engine lathe and some of the operations that can be performed on it will be used to introduce numerous terms and definitions that are applicable to all types of machining operations. This description is therefore necessarily quite lengthy, but it is important even for those familiar with machining operations because of the international terminology used.

For the present purposes the term *machining* will be taken to mean any process in which material is removed gradually from a workpiece, including metal cutting with single-point and multipoint tools and grinding with abrasive wheels.

For each machining operation, equations are developed to estimate the time taken to perform the operation and the power required. At the end of the chapter a summary of these equations is presented, together with typical characteristics of the machines described (including speed range, feed range, power, efficiency, size, and accuracy) and characteristics of various work materials.

1.3 MACHINES USING SINGLE-POINT TOOLS

1.3.1 Engine Lathe (Center Lathe)

An engine lathe is shown diagrammatically in Figure 1.3a; it consists of a horizontal bed supporting the headstock, the tailstock, and the carriage. All machine tools must have a means of supporting or holding the workpiece. In Figure 1.3 the workpiece is gripped at one end by a chuck mounted on the end of the main spindle of the machine and is supported at the other end by a center mounted in the tailstock. The tailstock can be clamped at various positions along the bed to accommodate workpieces of various lengths. Short workpieces need only be gripped by the chuck and, as a rule-of-thumb, parts with a length to diameter ratio of less than three to one need be supported in the chuck only.

Primary motion, the rotation of the workpiece (motion C′), is provided by the movement of a series of gears driving the main spindle, the gears being driven by an electric motor mounted at the rear of the machine. The main spindle and the gears are all mounted in the headstock. Levers on the front of the headstock allow various rotational speeds to be selected.

The single-point cutting tool is held in a toolholder or tool post, which is mounted on a cross slide, which in turn is mounted on the carriage. The carriage is driven along the bed (motion Z) by a lead screw (for screw cutting) or a rack, pinion gear, and feed rod (for turning); both the lead screw and the feed rod are connected to the main spindle through a train of gears. Alternatively the carriage can remain stationary on the bed, and the gear train can be used to drive the toolholder across the carriage (motion X) using a lead screw in the cross slide.

Figure 1.3b shows a cylindrical surface being generated on a workpiece by the rotation of the workpiece (-C′ motion) and the movement of the carriage along the lathe bed (-Z motion); this operation is known as cylindrical turning.

The feed motion setting on the lathe is the distance moved by the tool during each revolution of the workpiece. Once chosen, the feed setting remains constant regardless of the spindle speed because of the geared drive between the main spindle and the feed rod. The feed f for all machine tools is defined as the displacement of the tool relative to the workpiece, in the direction of feed motion, per stroke or per revolution of the workpiece or tool. Thus, to turn a cylindrical surface of length l_w, the number of revolutions of the workpiece is l_w/f, and the machining time t_m, is given by

$$t_m = \frac{l_w}{f n_w} \tag{1.1}$$

where t_m, is the rotational frequency of the workpiece.

It should be emphasized at this point that n_w, is the time for one pass of the tool (one cut) along the workpiece. This single pass does not necessarily mean, however, that the machining operation is completed. If the first cut is designed to remove a large amount of material at high feed (roughing cut), the forces generated during the operation will probably have caused significant deflections

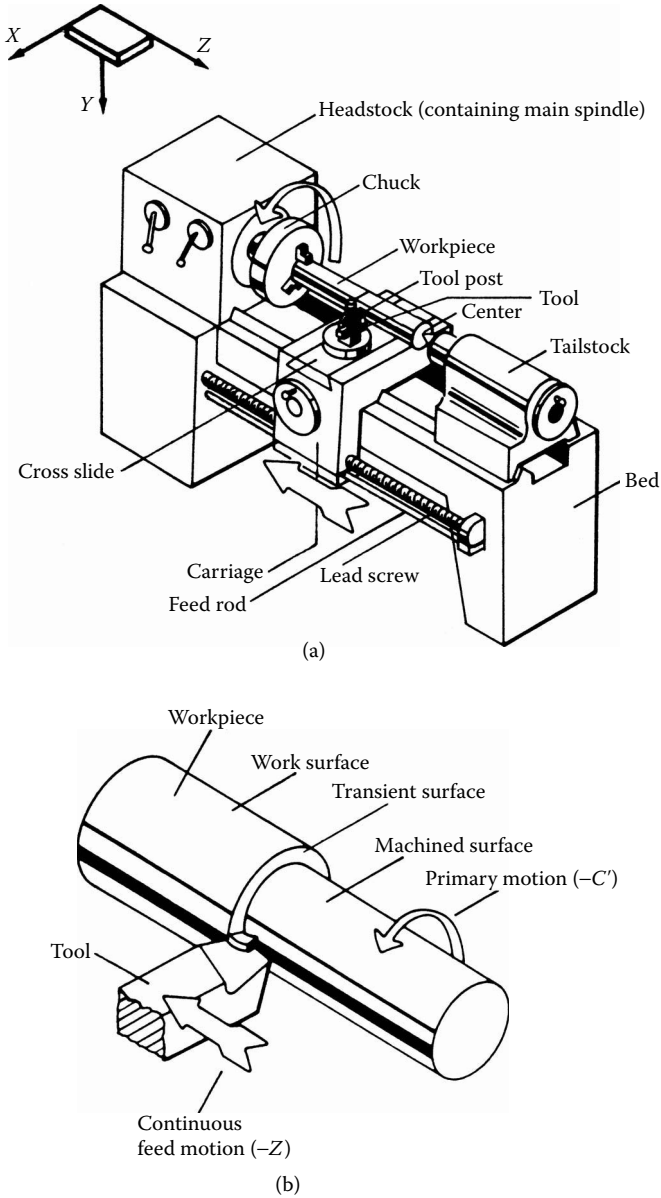


FIGURE 1.3 (a) An engine lathe; (b) cylindrical turning on an engine lathe.

in the machine structure. The resulting loss of accuracy will necessitate a further machining operation at low feed (finish cut) to bring the workpiece diameter within the limits specified and provide a smooth machined surface. For these reasons, it is usual to machine the workpiece oversize deliberately during the

roughing cut, leaving a small amount of material that will subsequently be removed during the finishing cut.

Before discussing the operation of the lathe further, it will be helpful to describe some of the features of the single-point tool used in the lathe and in several other types of machine tools.

1.3.2 Single-Point Tools

Single-point tools are cutting tools having one cutting part (or chip-producing element) and one shank. They are commonly used in lathes, turret lathes, planers, shapers, boring mills, and similar machine tools. A typical single-point tool is illustrated in Figure 1.4. The most important features are the cutting edges and adjacent surfaces. These are shown in the figure and defined as follows:

1. The face is the surface or surfaces over which the chip flows.
2. The flank is the tool surface or surfaces over which the surface produced on the workpiece passes.
3. The cutting edge is that edge of the face which is intended to perform cutting. The tool major cutting edge is that entire part of the cutting edge which is intended to be responsible for the transient surface on the workpiece. The tool minor cutting edge is the remainder of the cutting edge.
4. The corner is the relatively small portion of the cutting edge at the junction of the major and minor cutting edges; it may be curved or straight, or it may be the actual intersection of these cutting edges.

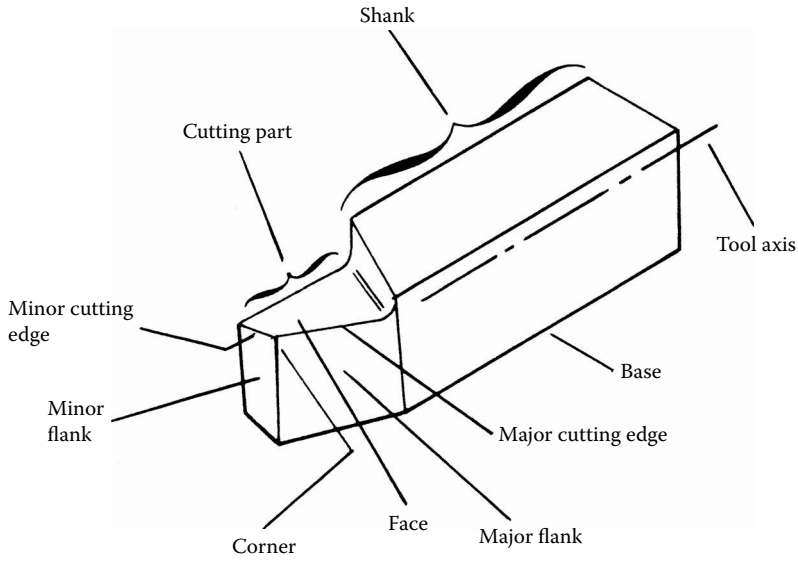


FIGURE 1.4 Typical single-point tool.

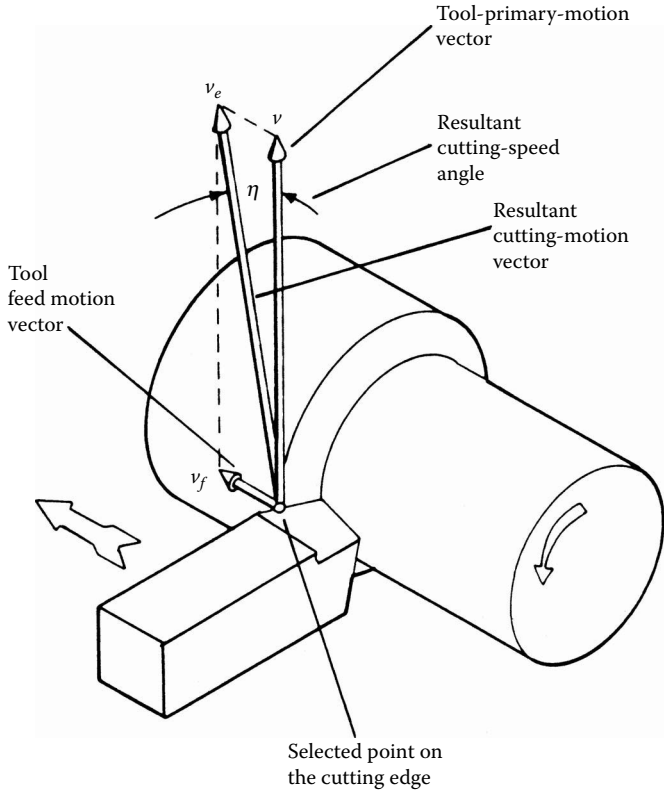


FIGURE 1.5 Resultant cutting motion in cylindrical turning.

In general, when a tool is applied to a workpiece, its motion relative to the workpiece has two components:

1. The motion resulting from the primary motion of the machine tool, which can be called the primary motion of the tool
2. The motion resulting from feed motion of the machine (Figure 1.5)

The resultant of these two tool motions is called the resultant cutting motion and is defined as the motion resulting from simultaneous primary and feed motions.

It should be noted that in machine tools where the feed is applied while the tool is not engaged with the workpiece (as in shaping or planing, for example), the resultant cutting motion is identical to the primary motion. Where the feed motion is applied continuously, the angle between the direction of primary motion and the resultant cutting direction is called the resultant cutting-speed angle η. This angle is usually extremely small and for most practical purposes can be assumed to be zero. Further, the cutting speed v, the instantaneous velocity of

the primary motion of the selected point on the cutting edge relative to the workpiece, can vary along the major cutting edge. The feed speed v_f, the instantaneous velocity of the feed motion of the selected point on the cutting edge relative to the workpiece, is constant.

Finally, the resultant cutting speed v_e, the instantaneous velocity of the resultant cutting motion of the selected point on the cutting edge relative to the workpiece, is given by

$$v_e = \frac{v}{\cos \eta} \tag{1.2}$$

but since for most practical operations η is very small, it can generally be assumed that

$$v_e = v \tag{1.3}$$

One of the important tool angles when considering the geometry of a particular machining operation is the angle in Figure 1.6 called the major cutting-edge angle κ_r. The thickness of the layer of material being removed at the selected point on the cutting edge, known as the undeformed chip thickness a_c, significantly affects the power required to perform the operation. Strictly, this dimension should be measured both normal to the cutting edge and normal to the resultant cutting direction. However, for all practical purposes, since η is small, as described above, a_c, can be measured normal to the direction of primary motion; thus in Figure 1.6 and all subsequent figures, a_c will be measured this way. From Figure 1.6, therefore, a_c is given by $a_f \sin \kappa_r$, where a_f is the feed engagement, the instantaneous engagement of the tool cutting edge with the workpiece measured in the direction of feed motion. For single-point cutting operations a_f is equal to the feed f, and therefore

$$a_c = f \sin \kappa_r \tag{1.4}$$

The cross-sectional area A_c of the layer of material being removed (cross-sectional area of the uncut chip) is approximately given by

$$A_c = f a_p \tag{1.5}$$

where a_p is the back engagement, previously known as depth of cut. The back engagement is the instantaneous engagement of the tool with the workpiece, measured perpendicular to the plane containing the directions of primary and feed motion (Figure 1.5). In general the back engagement determines the depth of material removed from the workpiece in a single-point cutting operation.

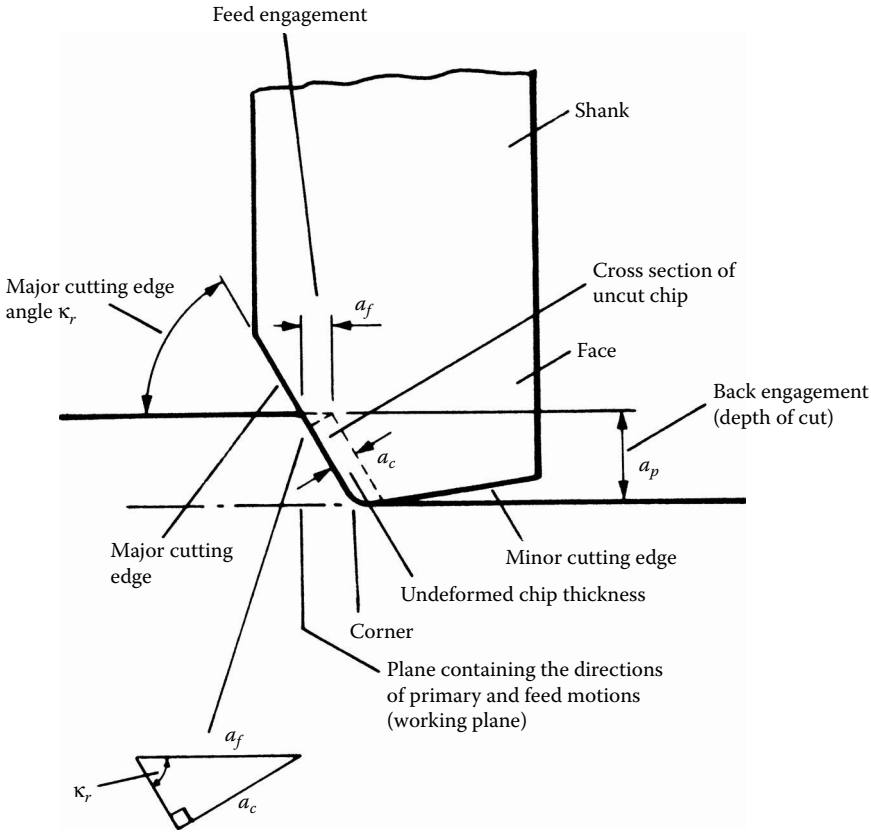


FIGURE 1.6 Single-point tool operation, where $a_c = a_f \sin_r$.

1.3.3 Typical Lathe Operations

Figure 1.7 illustrates five typical lathe operations: cylindrical turning, facing, boring, external threading, and cutoff. In each case the primary motion and the feed motion, together with certain other terms and dimensions, are indicated. In any machining operation the workpiece has three important surfaces:

1. The work surface, the surface on the workpiece to be removed by machining
2. The machined surface, the desired surface produced by the action of the cutting tool
3. The transient surface, the part of the surface formed on the workpiece by the cutting edge and removed during the following cutting stroke, during the following revolution of the tool or workpiece, or, in other cases (as, for example, in a thread-turning operation) (Figure 1.7d) during the following pass of the tool

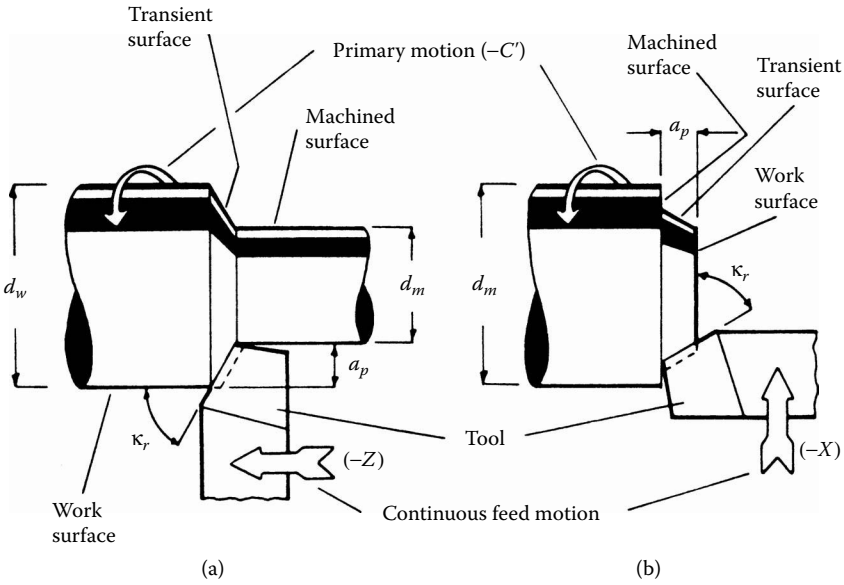


FIGURE 1.7 Lathe operations. (a) Cylindrical turning; (b) facing; (c) boring; (d) external threading; (e) parting and cutoff.

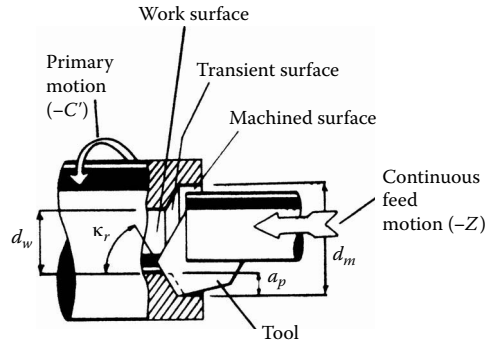
In Figure 1.7a, which shows the geometry of a cylindrical-turning operation, the cutting speed at the tool corner is given by $d_m n_w$, where n_w is the rotational frequency of the workpiece, and d_m is the diameter of the machined surface. Thus the average, or mean, cutting speed v_{av} is given by

$$v_{av} = \frac{\pi n_w \left(d_w + d_m\right)}{2} \tag{1.6}$$

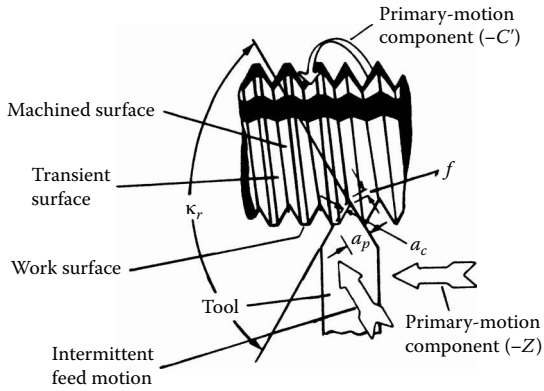
The metal removal rate Z_w is the product of the mean cutting speed and the cross sectional of the uncut chip, A_c. Thus

$$\begin{aligned} Z_w &= A_c v_{av} \\ &= \frac{\pi a_f a_p n_w \left(d_w + d_m\right)}{2} \\ &= \pi f a_p n_w \left(d_m + a_p\right) \end{aligned} \tag{1.7}$$

The same result could have been obtained by dividing the total volume of metal removed by the machining time t_m.



(c)



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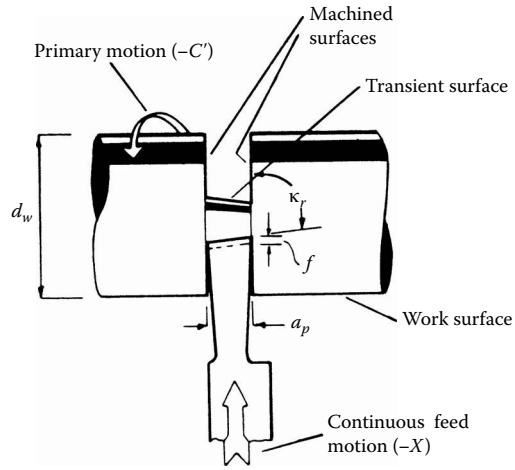


(e)

FIGURE 1.7 (continued).

For operations where the back engagement a_p is small compared to the diameter of the machined surface d_m, the metal removal rate is approximately given by

$$Z_w \cong \pi f a_p n_w d_m \tag{1.8}$$

For a given work material machined under given conditions, the energy required to remove a unit volume of material, p_s, can be measured. This factor is mainly dependent on the work material. The power P_m required to perform any machining operation can be obtained from

$$P_m = p_s Z_w \tag{1.9}$$

Finally, if the overall efficiency of the machine tool motor and drive systems is denoted by η_m, the electrical power P_e consumed by the machine tool is given by

$$P_e = \frac{P_m}{\eta_m} \tag{1.10}$$

Approximate values of p_s, for various work materials and various values of the undeformed chip thickness are presented at the end of this chapter.

An operation in which a flat surface is generated by an engine lathe is shown in Figure 1.7b and can be performed by feeding a tool in a direction at right angles (-X motion) to the axis of workpiece rotation. In this operation, known as *facing*, the cutting speed at the tool corner varies from a maximum at the beginning of the cut to zero when the tool reaches the center of the workpiece. Clearly this operation can only be performed when the workpiece does not require support by the tailstock center.

The undeformed chip thickness a_c and the cross-sectional area of the uncut chip A_c are given, as in cylindrical turning, by Equation 1.4 and Equation 1.5, respectively.

The machining time t_m is given by

$$t_m = \frac{d_m}{2 f n_w} \tag{1.11}$$

The maximum cutting speed $v_{\max}$ and the maximum metal removal rate $Z_{w_{\max}}$ are given by

$$v_{\max} = \pi n_w d_m \tag{1.12}$$

$$Z_{w_{\max}} = \pi f a_p n_w d_m \tag{1.13}$$

Figure l.7c shows an internal cylindrical surface being generated on a lathe. This operation is termed *boring* and can only be used to enlarge an existing hole in the workpiece. If the diameter of the work surface is d_w and the diameter of the machined surface is d_m, the mean cutting speed is given by Equation 1.6 and the metal-removal rate by

$$Z_w = \pi f a_p n_w \left(d_m - a_p\right) \tag{1.14}$$

Finally the machining time t_m is given by Equation 1.1 if l_w is taken as the length of the hole to be bored.

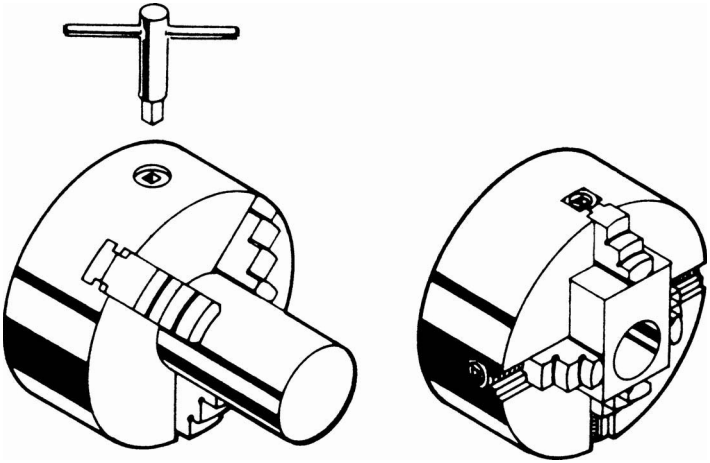
The lathe operation illustrated in Figure l.7d is known as external threading, or screw cutting. In this operation the primary motion of the tool is considered to be a combination of the motions -C′ and -Z. This motion generates a helix on the workpiece and is obtained by setting the gears that drive the lead screw to give the required pitch of the machined threads. The machining of a thread necessitates several passes of the tool along the workpiece, each pass removing a thin layer of metal from one side of the thread. The feed is applied in increments, after each pass of the tool, in a direction parallel to the machined surface. In calculating the production time, allowance must be included for the time taken to return the tool to the beginning of the cut, to increment the feed, and to engage the lathe carriage with the lead screw.

The last lathe operation to be illustrated (Figure l.7e) is used when the finished workpiece is to be separated from the bar of material gripped in the chuck. It is known as a parting, or cutoff, operation and produces two machined surfaces simultaneously. As with a facing operation, the cutting speed and hence the metal removal rate varies from a maximum at the beginning of the cut to zero at the center of the workpiece. The machining time is given by Equation 1.11 and the maximum metal removal rate by Equation 1.13.

1.3.4 Work and Tool Holding in an Engine Lathe

In the most common method of work holding, the chuck has either three or four jaws (Figure 1.8) and is mounted on the end of the main spindle. A three-jaw chuck is used for gripping cylindrical workpieces when the operations to be performed are such that the machined surface is concentric with the work surfaces. The jaws have a series of teeth that mesh with spiral grooves on a circular plate within the chuck. This plate can be rotated by the key inserted in the square socket, resulting in simultaneous radial motion of the jaws. Since the jaws maintain an equal distance from the chuck axis, cylindrical workpieces are automatically centered when gripped.

With the four-jaw chuck, each jaw can be adjusted independently by rotation of the radially mounted threaded screws. Although accurate mounting of a workpiece can be quite time-consuming, a four-jaw chuck is often necessary for noncylindrical workpieces.



(a) (b)

FIGURE 1.8 Lathe work holding using chucks. (a) Three-jaw (self-centering) chuck; (b) independent four-jaw chuck.

For very complicated shapes, a circular faceplate can be used. The faceplate has radial slots that provide a means of bolting the workpiece to the faceplate.

For small lathes employed extensively for work on material provided in bar form, collets are often used. These collets are effectively split sleeves that fit snugly over the workpiece and have a taper on their outer surface. Drawing the collet into a matching tapered hole in the end of the spindle has the effect of squeezing the collet and gripping the workpiece. In general collets are not usually suitable for gripping bar materials larger than 50 mm in diameter. The range of standard collets available includes those with gripping surfaces suitable for non-round bar materials, such as hexagonal and square section bar stock materials.

For accurate turning operations or in cases where the work surface is not truly cylindrical, the workpiece can be turned between centers. This form of work holding is illustrated in Figure 1.9. Initially the workpiece has a conical center hole drilled at each end to provide location for the lathe centers. Before supporting the workpiece between the centers (one in the headstock and one in the tailstock), a dog (a clamping device) is secured at the headstock end. The dog is arranged so that the tip is inserted in a slot in the drive plate mounted on the main spindle, ensuring that the workpiece will rotate with the spindle.

The simplest form of tool holder is illustrated in Figure 1.10 and is suitable for holding one single-point tool. Immediately below the tool is a curved block resting on a concave spherical surface; this method of support provides an easy way of inclining the tool so that its corner is at the correct height for the machining operation. In the figure the tool post is shown mounted on a compound rest. The rest is a small slideway that can be clamped in any angular position in the horizontal plane and is mounted on the cross slide of the lathe. The compound

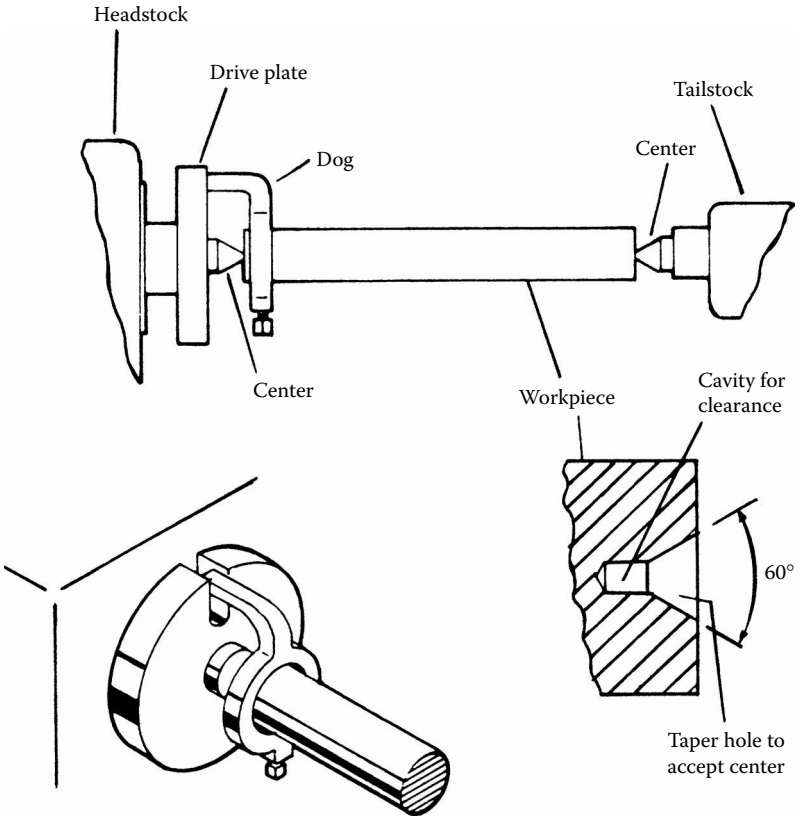


FIGURE 1.9 Work holding when turning between centers.

rest allows the tool to be hand-fed at an oblique angle to the lathe bed and is required, for example, in screw-threading operations and the machining of short tapers or chamfers.

Another common form of tool post is shown in Figure 1.11; it also would be mounted on the compound rest. This four-way tool post can, as its name suggests, accommodate as many as four cutting tools. Any cutting tool can be quickly brought into position by unlocking the tool post with the lever provided, rotating the tool post, and, finally, reclamping with the lever. Variations on this type of tool post with quick-change toolholders are commonly used and a number of proprietary tooling systems are available.

1.3.5 Other Types of Lathes

The engine lathe is the most common machine tool used in low-production work. Several other kinds of lathes are available: for medium-production work, turret lathes are widely employed. In a turret lathe the tailstock is replaced with a rotary-indexing, hexagonal turret that can be driven along the bed by the lead screw. A

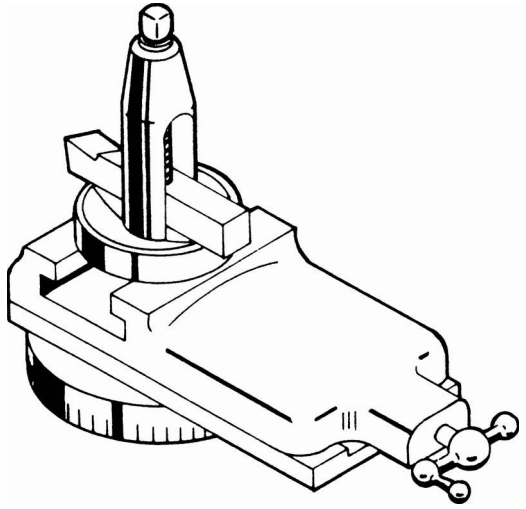


FIGURE 1.10 Typical lathe tool post and compound rest.

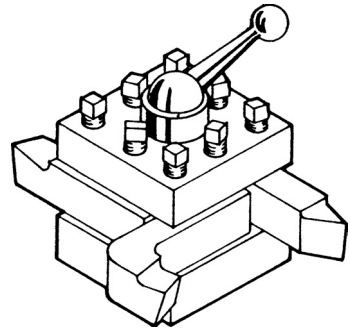


FIGURE 1.11 Four-way tool post.

variety of tools can be mounted on the faces of the turret (in some turret lathes two or more tools can be mounted on the one face) and are brought into operation by manually indexing the turret and engaging the feed drive.

Single-spindle and multi-spindle automatic lathes are suitable for high-volume or mass production of small components machined from work material in bar form. Specially machined cams control the various motions of these lathes, and the operations are completely automatic, including the gradual feeding of the workpiece through the hollow spindle to the collet. The machine needs attention only when a new bar of material is required. Items such as small screws needed in large quantities are manufactured on this type of lathe. More descriptions of multi-spindle automatic lathes and their operation can be found in Chapter 11.

A wide range of programmable numerically controlled (nc) lathes and turning centers are also available. The basic cutting motions are the same as above and additional descriptions of these machines can be found in Chapter 11.

1.3.6 Vertical-Boring Machine (Vertical Borer)

A horizontal-spindle lathe is not suitable for turning heavy, large-diameter workpieces. The axis of the machine spindle would have to be so elevated that a machinist could not easily reach the tool- and work-holding devices. In addition, it would be difficult to mount the workpiece on a vertical faceplate or support it between centers; for this reason a machine that operates on the same principle as a lathe but has a vertical axis is used and is known as a vertical-boring machine (Figure 1.12). Like the lathe, this machine rotates the workpiece (motion C′) and applies continuous, linear feed motion to the tool. This motion can be either at right angles to the axis of workpiece rotation (motion X) or parallel to it (motion Z).

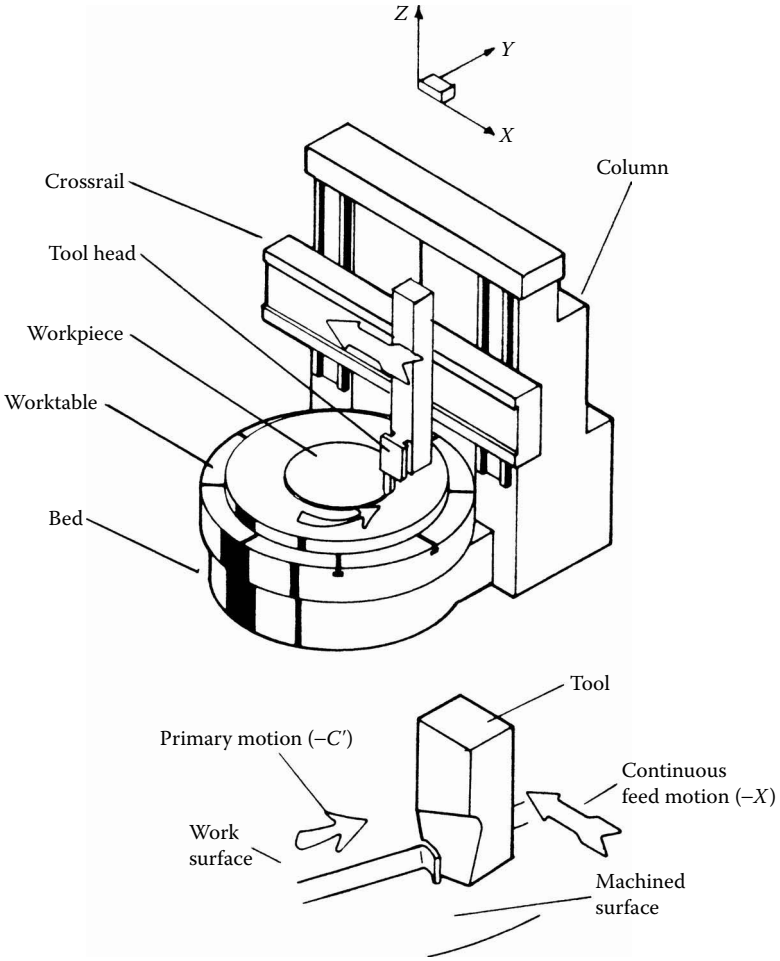


FIGURE 1.12 Facing on a vertical-boring machine.

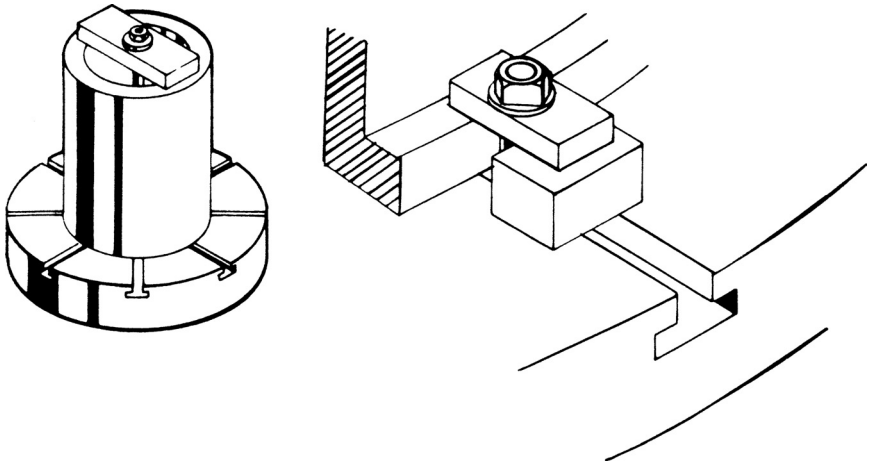


FIGURE 1.13 Work holding in vertical boring machines.

Single-point tools are employed and mounted in a toolholder similar to the four-way tool post shown in Figure 1.11 but without the rapid-indexing feature. The operations carried out are generally limited to turning (-Z motion), facing (-X motion), and boring (-Z motion). These operations were illustrated in Figure l.7a to c; the geometry described and equations developed still apply.

The horizontal work-holding surface, which facilitates the positioning of large workpieces, consists of a rotary table having radial T slots for clamping purposes. Two typical work-holding methods are illustrated in Figure 1.13.

1.3.7 Horizontal-Boring Machine (Horizontal Borer)

The last type of machine described here that uses single-point tools and has a rotary primary motion is a horizontal-boring machine (Figure 1.14). This machine is needed mostly for heavy noncylindrical workpieces in which an internal cylindrical surface is to be machined. In general, the words *horizontal* or *vertical* are used when describing a machine tool to refer to the orientation of the machine spindle that provides primary motion (main spindle). Thus, in the horizontal borer the main spindle is horizontal.

The principal feature of the machine is that the workpiece remains stationary during machining, and all the generating motions are applied to the tool. The most common machining process is boring and is shown in the figure; boring is achieved by rotating the tool, which is mounted on a boring bar connected to the spindle (motion C), and feeding the spindle, boring bar, and tool along the axis of rotation (motion Z). The machine tool motions that can be used to move the workpiece are for positioning of the workpiece and are not generally employed while machining is taking place. A facing operation is carried out by using a special toolholder (Figure 1.15) that feeds the tool radially as it rotates.

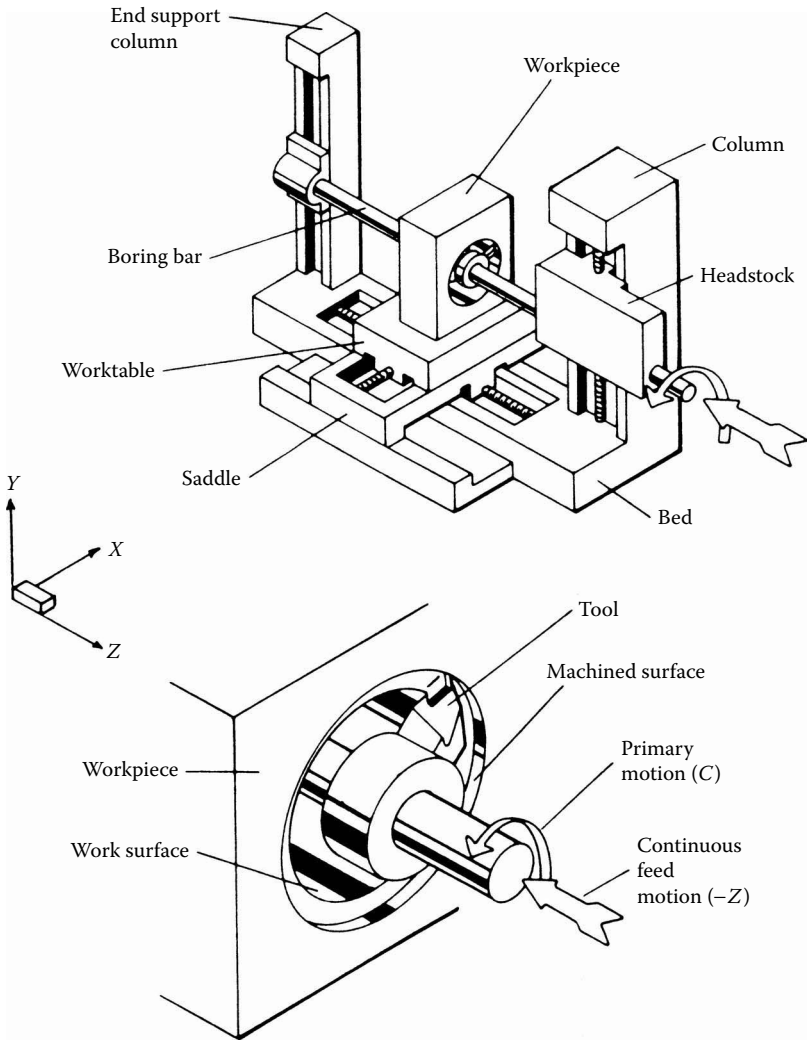


FIGURE 1.14 Boring on a horizontal-boring machine.

The worktable has T slots to facilitate clamping of the workpiece. Several common methods of using these T slots are shown in Figure 1.16.

Again, the equations developed earlier for the undeformed chip thickness, the machining time, and the metal removal rate in boring and facing apply.

1.3.8 Shaping Machine (Shaper)

The shaper is a small machine on which the primary motion is linear (Figure 1.17). The single-point tool is gripped in a toolhead mounted on the end of a ram. The ram is made to move backward and forward (X motion) either by a mechanical

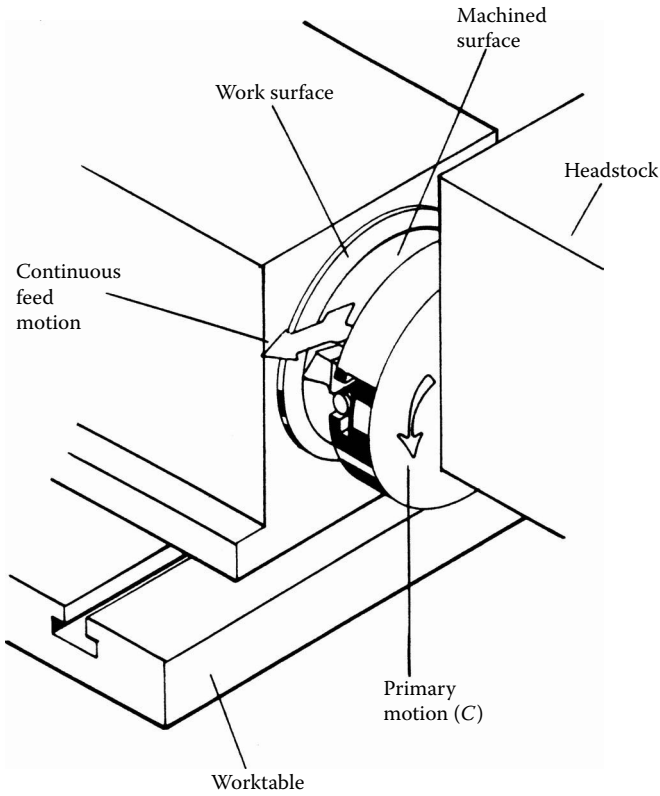


FIGURE 1.15 Facing on a horizontal-boring machine.

drive system or a hydraulic piston and cylinder. The cutting stroke is the forward stroke, and with either mechanical or hydraulic shapers, the forward ram speed is slower than the speed on the return stroke, causing the production time to be reduced as much as possible. A quick-return mechanism often used in mechanical shapers is shown in Figure 1.18. In all shapers the length of the stroke can be adjusted to suit the particular workpiece being machined. The feed is applied to the workpiece in increments at the end of the return stroke of the ram by a ratchet and-pawl mechanism driving the lead screw in the crossrail.

Shapers are most commonly used to machine flat surfaces on small components and are only suitable for low-batch quantities. For the machining of a horizontal surface (Figure 1.17), the workpiece is fed horizontally (Y motion); for vertical surfaces, the workpiece is fed vertically (Z motion).

Typical tool- and work-holding methods are illustrated in Figure 1.19, where it can be seen that the toolhead is similar to the tool post and compound rest used on a lathe. The toolhead can be rotated and clamped in various positions in the vertical plane to allow inclined surfaces to be generated by hand feeding of the tool. An essential feature of the shaper toolhead is the clapper box. Effectively the

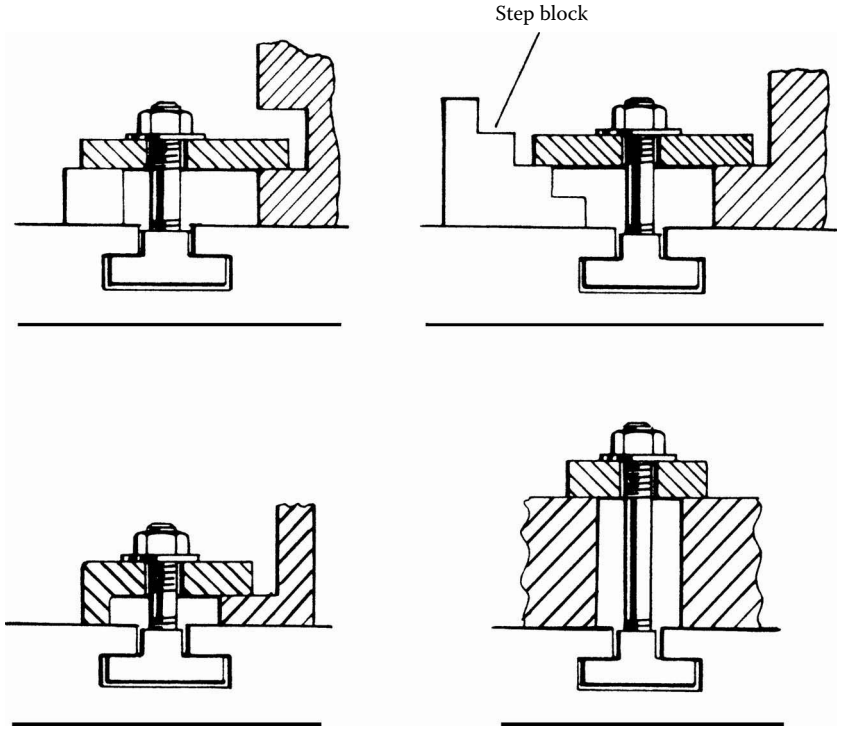


FIGURE 1.16 Work holding methods for machine tables having T slots.

tool post is pivoted on a horizontal pin and the tool is free to rotate forward, thereby lifting the tool corner during the return stroke of the ram. This action is brought about simply by the force exerted by the workpiece on the tool as the tool is dragged backward across the work surface. The workpiece is generally conveniently held in a vise bolted to the surface of a table provided with T slots for this purpose.

The geometries when shaping horizontal, vertical, and inclined flat surfaces are shown in Figure 1.20. For a surface of width b_w the machining time t_m is given by

$$t_m = \frac{b_w}{fn_r} \tag{1.15}$$

where n_r is the frequency of reciprocation or cutting strokes, and f is the feed.

The metal removal rate Z_w during cutting will be given by

$$Z_w = A_c v = f a_p v \tag{1.16}$$

where v is the cutting speed, and a_p is the back engagement.

The undeformed chip thickness a_c will be given by

$$a_c = f \sin \kappa_r \tag{1.17}$$

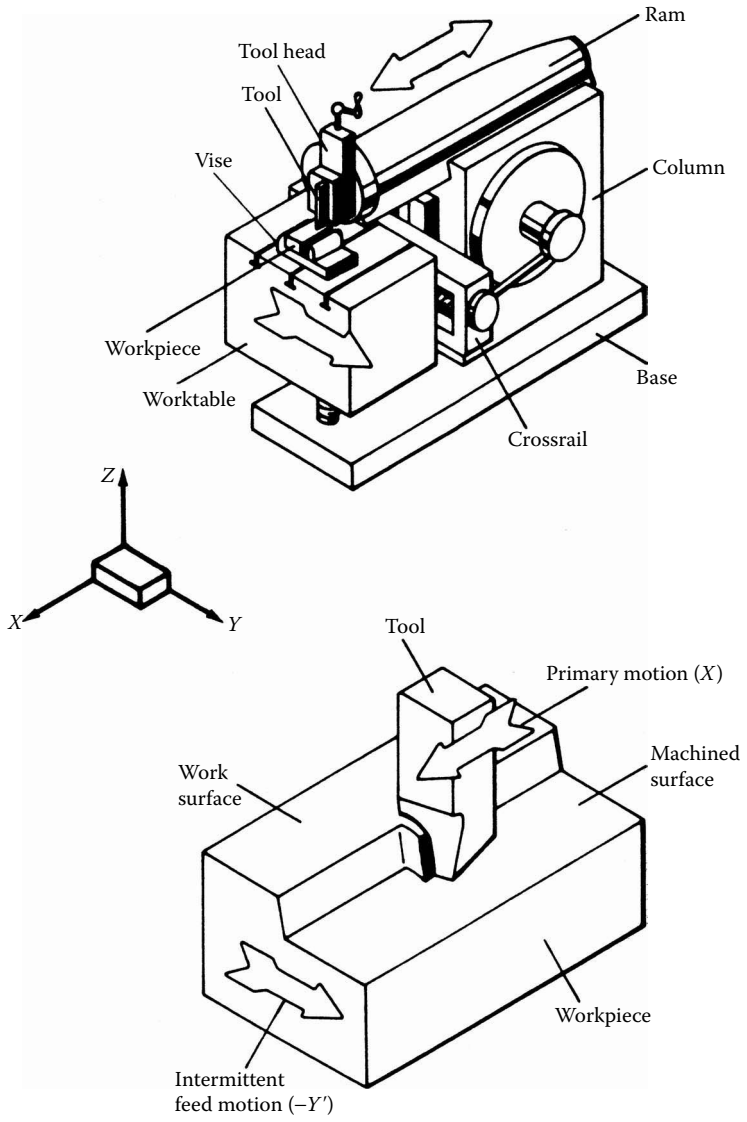


FIGURE 1.17 Production of flat surfaces on a shaper.

1.3.9 Planing Machine (Planer)

The shaper is unsuitable for generating flat surfaces on very large parts because of limitations on the stroke and overhang of the ram. This problem is solved in the planer (Figure 1.21) by applying the linear primary motion to the workpiece (motion X′) and feeding the tool at right angles to this motion (motion Y or Z). The primary motion is normally accomplished by a rack-and-pinion drive using

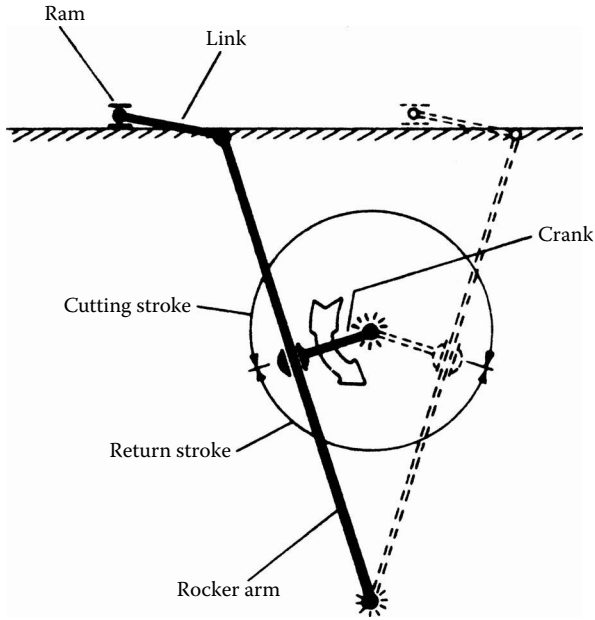


FIGURE 1.18 Quick-return mechanism for a mechanical shaper.

a variable-speed motor. As with the shaper, the tool posts are mounted on clapper boxes to prevent interference between the tools and workpiece on the return stroke, and the feed motion is intermittent. The work is held on the machine table using the T slots provided. The machining time, metal removal rate, and undeformed chip thickness can be estimated using the equations developed for the shaper.

The planer is the last of the machine tools employing single-point cutting tools to be described here. The next section describes machines designed to apply multipoint cutting tools to the workpiece.

1.4 MACHINES USING MULTIPOINT TOOLS

1.4.1 Multipoint Tools

A multipoint tool can be regarded as a series of two or more cutting parts (chip-producing elements) secured to a common body. The majority of multipoint tools (milling cutters, drills, etc.) are intended to be rotated and have either a taper (conical) or parallel (cylindrical) shank for holding purposes or a bore through which a spindle or arbor can be inserted. The terms such as *face*, *flank*, and *cutting edges*, defined earlier for single-point tools, are still applicable, and the cutting action at a selected point on one of the cutting edges is the same.

The common multipoint tools (drills, reamers, milling cutters, and broaches) will be introduced along with descriptions of the machine tools on which they are most often used.

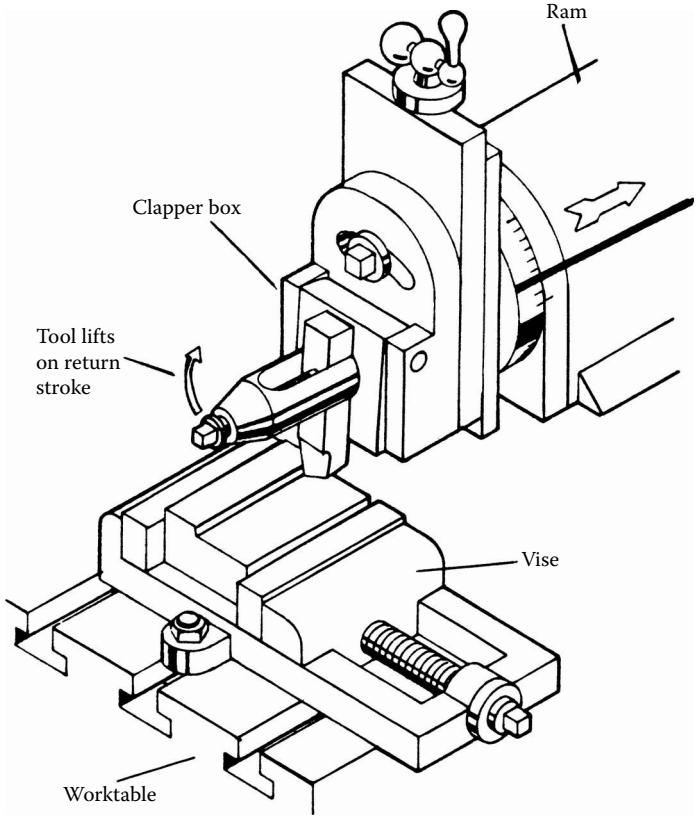


FIGURE 1.19 Tool and work holding on a shaper.

1.4.2 Drilling Machine (Drill Press)

A drill press (Figure 1.22) can perform only those operations where the tool is rotated (motion C) and fed along its axis of rotation (motion Z). The workpiece always remains stationary during the machining process. On many drill presses the tool is fed by the manual operation of a lever to the right of the head. Both the worktable and the head can be raised and lowered to accommodate workpieces of different heights.

The most common operation performed on this machine is drilling with a twist drill to generate an internal cylindrical surface. A twist drill with a taper shank, together with the geometry of the drilling operation, is shown in Figure 1.23. This tool has two cutting edges, each of which is expected to remove its share of the work material. Thus the feed per tooth (the depth of material removed by each tooth and measured parallel to the direction of feed motion) is the feed engagement a_f and is equal to ½ of the feed *f*. By geometry therefore

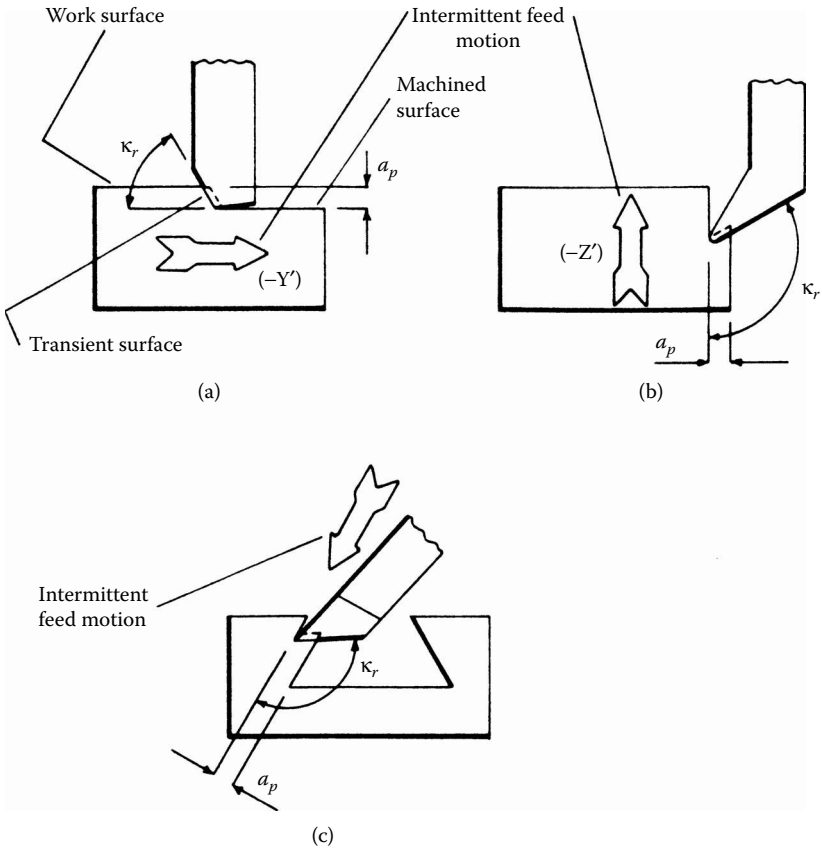


FIGURE 1.20 Shaping operations. (a) Horizontal surface; (b) vertical surface; (c) inclined surface.

$$a_c = \frac{f}{2} \sin \kappa_r \tag{1.18}$$

where κ_r is the major cutting-edge angle.

The machining time t_m is given by

$$t_m = \frac{l_w}{f n_t} \tag{1.19}$$

where l_w is the length of the hole produced, and n_t is the rotational frequency of the tool. For blind holes l_w is the depth of holes, but for through holes an allowance must be made for the drill point to clear the exit side of the workpiece. In this case l_w is given by

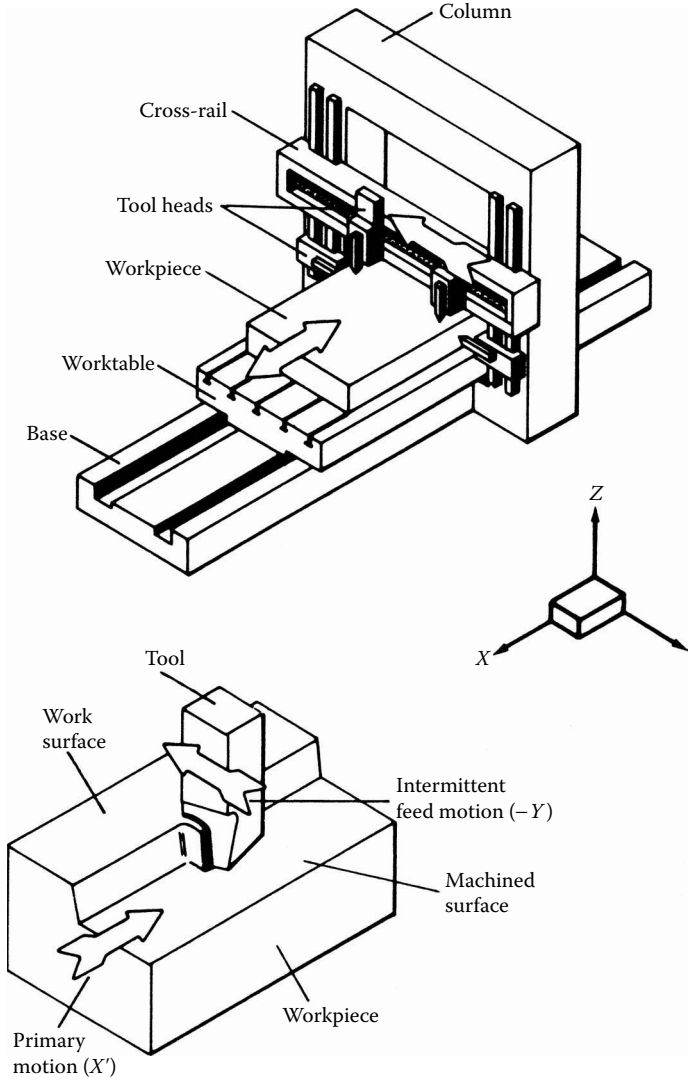


FIGURE 1.21 Production of flat surfaces on a planer.

$$l_w = t_w + \frac{a_p}{2\tan\kappa_r} = t_w + \frac{d_m}{2\tan\kappa_r} \tag{1.20}$$

where

t_w = thickness of the workpiece

a_p = the work engagement (in this case equal to the drill diameter, d_m)

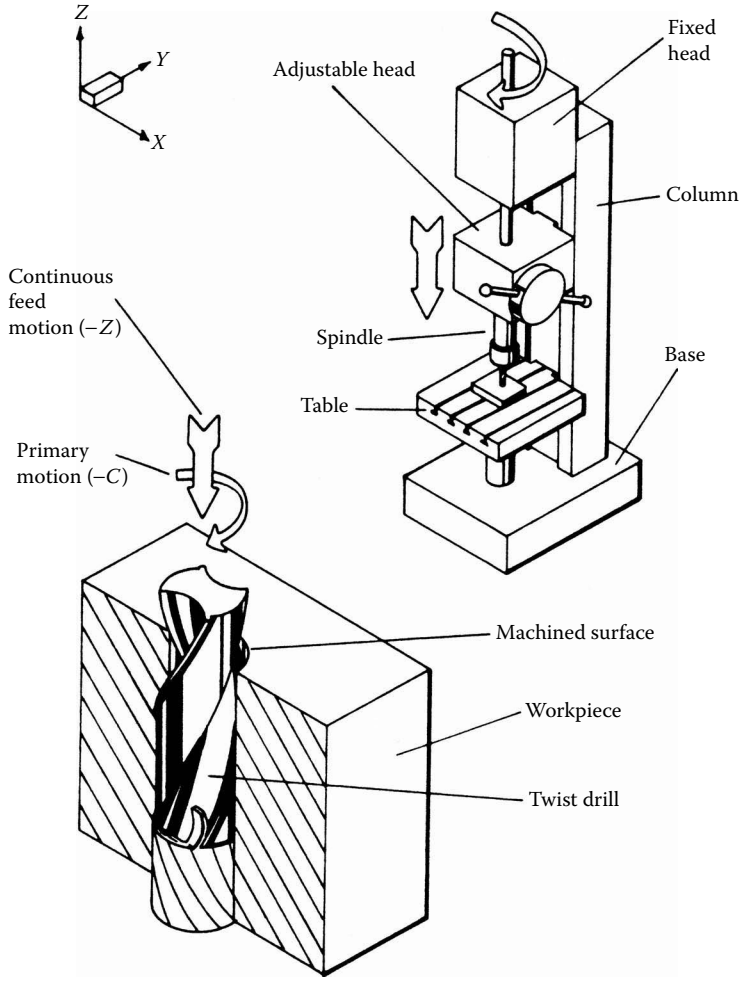


FIGURE 1.22 Drilling on a drill press.

The metal removal rate Z_w may be obtained by multiplying the feed speed v_f by the cross-sectional area of the hole produced. Thus

$$Z_w = \frac{\pi}{4} d_m^2 v_f = \frac{\pi f d_m^2 n_t}{4} \tag{1.21}$$

where d_m is the diameter of the machined surface. If an existing hole of diameter d_w is being enlarged,

$$Z_w = \frac{\pi f \left(d_m^2 - d_w^2 \right) n_t}{4} \tag{1.22}$$

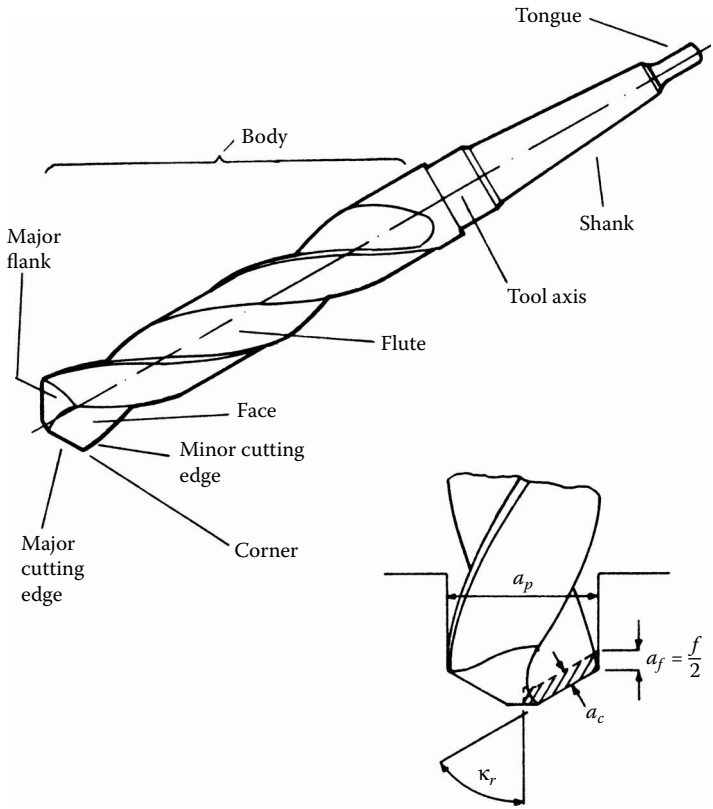


FIGURE 1.23 Twist drill, where $a_c = a_f \sin_{r}$

Clearly the cutting speed will be a maximum at either corner (the outer radius of the major cutting edges) and will be zero at the tip of the drill, which is in the form of a short chisel edge. In drilling a new hole, this chisel edge must force its way through the work material, effectively pushing the material outward to be removed by the cutting edges. The poor cutting conditions in this region have little effect on the quality of the hole produced, which is mainly determined by the conditions at the minor cutting edges. The chips removed by the cutting edges take a helical form and travel up the drill flutes.

Twist drills are usually considered suitable for machining holes having a length less than five times their diameter. Special drills requiring special drilling machines are available for drilling deeper holes and are not described here.

The workpiece is often held in a vise bolted to the machine worktable. The drilling of a concentric hole in a cylindrical workpiece, however, is often carried out on an engine lathe with the drill held either in the tailstock (for hand feeding) or in a special drill holder mounted on the carriage.

Large twist drills are usually provided with a taper shank, as shown in Figure 1.23. This shank is designed to be inserted in a corresponding taper hole

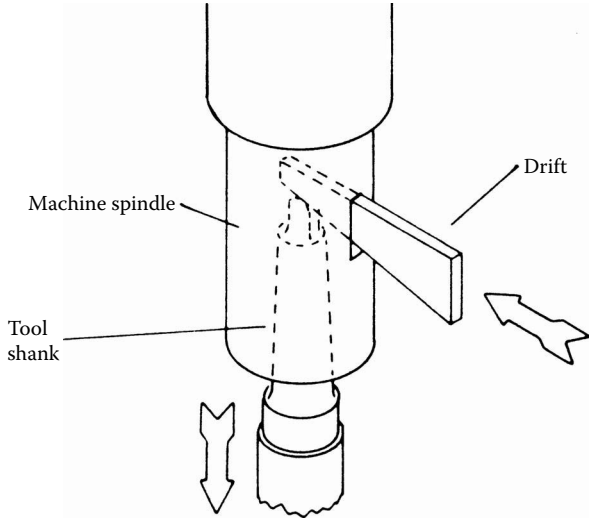


FIGURE 1.24 Releasing a taper-shank tool.

in the end of the machine spindle. The tongue on the end of the shank is inserted in a slot at the bottom of the hole in the spindle and prevents rotation of the drill relative to the spindle during machining. The drill is removed by tapping a wedge (drift) into the slot in the machine spindle, as illustrated in Figure 1.24.

Small twist drills have a parallel shank and are held in a three-jaw chuck of the familiar type used in hand drills. These chucks are provided with a taper shank for location in the drill-press spindle or in the tailstock of a lathe.

Several other machining operations can be performed on a drill press, and some of the more common ones are illustrated in Figure 1.25. The center-drilling operation produces a shallow, conical hole with clearance at the bottom. This center hole can provide a location for a lathe center when the workpiece is subsequently to be supported between centers (Figure 1.9) or can provide a guide for a subsequent drilling operation to prevent the drill point from "wandering" as the hole is started. The reaming operation is intended for finishing a previously drilled hole. The reamer is similar to a drill but has several cutting edges and straight flutes. It is intended to remove a small amount of work material only, but it considerably improves the accuracy and surface finish of a hole. The spot-facing operation is designed to provide a flat surface around the end of a hole and perpendicular to its axis; this flat surface provides a suitable seating for a washer and nut.

For large workpieces a radial-arm drilling machine is used (Figure 1.26). In this machine the drilling head and motor can be positioned along an arm that is free to swing in a horizontal plane about the column, allowing large areas to be covered. The radial-arm drilling machine is particularly suitable for drilling large numbers of holes in heavy workpieces.

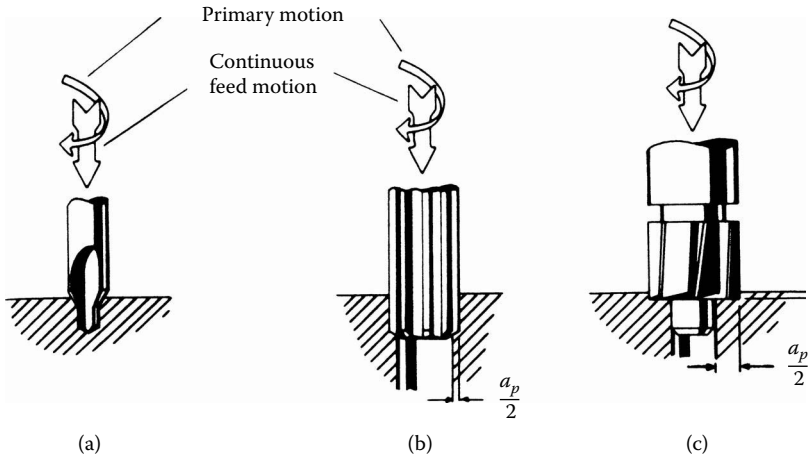


FIGURE 1.25 Some drill-press operations. (a) Center drilling; (b) reaming; (c) spot-facing.

1.4.3 Horizontal-Milling Machine (Horizontal Miller)

There are two main types of milling machines: horizontal and vertical. These words again refer to the orientation of the main spindle. In the horizontal-milling machine shown in Figure 1.27, the milling cutter is mounted on a horizontal arbor driven by the main spindle. The tools are therefore rotated (motion C) and the work fed continuously (motions X′ or Y′).

The simplest operation, slab milling, is used to generate a horizontal surface on the workpiece, as shown in Figure 1.27. The figure shows the conventional slab-milling operation; if the workpiece had been fed in the opposite direction, it would tend to climb onto the work surface, and this type of slab milling is called *climb* milling. Some evidence suggests that the forces and power consumption are less in climb milling than in conventional milling. However, high rigidity of the machine tool and work-and tool-holding devices is required for this operation.

The geometry in conventional slab milling is shown in Figure 1.28. The feed f which is equal to the distance moved by the workpiece during one revolution of the tool, is given by

$$f = \frac{v_f}{n_t} \tag{1.23}$$

where v_f is the feed speed of the workpiece, and n_t is the rotational frequency of the cutter. The feed engagement a_f, which is equal to the thickness of the chip removed by one tooth and measured parallel to the feed direction (feed per tooth), is given by f/N, where N is the number of teeth on the cutter. The maximum undeformed chip thickness, $a_{c\max}$ (measured normal to the direction of primary motion) is therefore given by

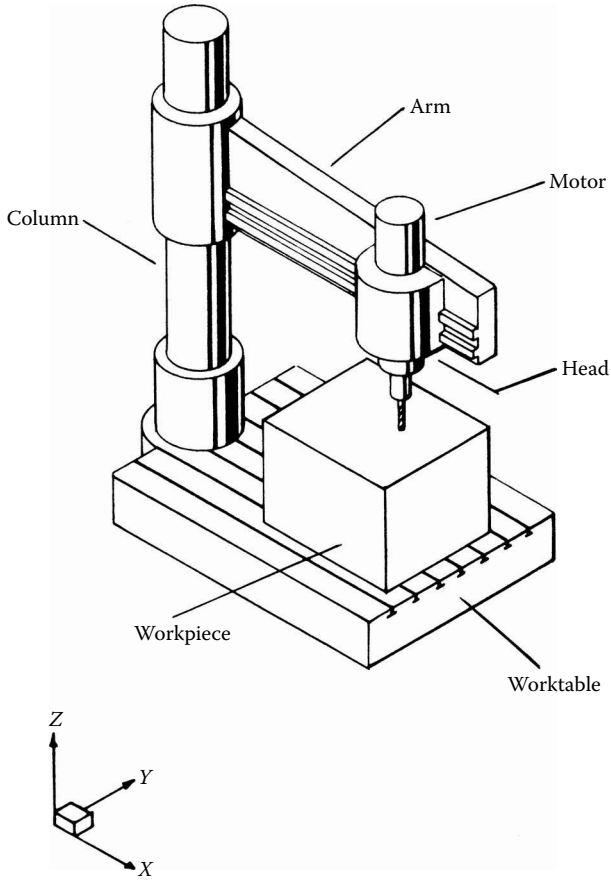


FIGURE 1.26 Radial-arm drill.

$$a_{c_{\max}} = \frac{v_f \sin\theta}{Nn_t} \tag{1.24}$$

where θ is given by (Figure 1.28).

$$\cos\theta = 1 - \frac{2a_e}{d_t} \tag{1.25}$$

where d_t is the diameter of the cutter, and a_e is the working engagement (the instantaneous engagement of the tool with the workpiece), measured in the plane containing the directions of primary and feed motions and perpendicular to the feed motion. In slab milling the working engagement is known as depth of cut.